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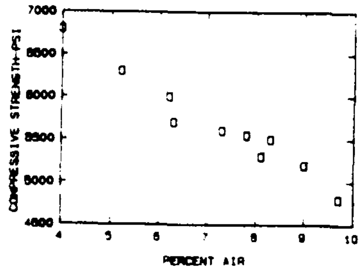
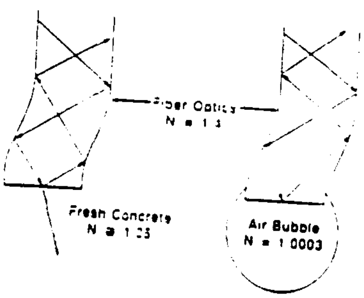
REVIEW OF MEASUREMENT TECHNIQUES AND PRINCIPLES WITH POTENTIAL APPLICATION FOR DEVELOPMENT OF DEVICE TO INDICATE ADEQUACY OF FRESH CONCRETE CONSOLIDATION





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13. ABSTRACT *(Maximum 200 words)*

A literature review and evaluation was performed to determine the potential of developing a device to measure degree of consolidation of freshly placed concrete in situ for improving quality control. Standard techniques exist to determine the air content of concrete as it comes from the mixer but not in situ. The features of an ideal device are discussed as a goal in the development of an optimum device. Measurement fundamentals such as resolution, accuracy, data storage, display, cost, ease of operation, etc. are discussed that relate to the development of such a device. The advantages and disadvantages of basing a device on the measurement of various phenomena such as electrical, optical, ultrasonic, nuclear, and other properties are discussed. Devices based on electrical resistivity, ultrasonics, and fiber optics show considerable promise, but more research is needed by independent organizations. It is believed that the technology exists to improve quality control and quality assurance measurements for in-place concrete. It should be possible to detect in situ whether the concrete needs revibration prior to hardening.

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PREFACE

This report was prepared at the Structures Laboratory (SL), US Army Engineer Waterways Experiment Station (WES), under the sponsorship of Headquarters, US Army Corps of Engineers, as part of Civil Works Investigation Studies Work Unit 31138, "New Technologies for Testing and Evaluating Concrete."

The study was conducted under the general supervision of Mr. Bryant Mather, Director, SL, and Mr. Kenneth L. Saucier, Chief, Concrete Technology Division (CTD), SL; and under the direct supervision of Mr. Steven A. Ragan, Chief, Engineering Mechanics Branch, CTD, and the Principal Investigator of this work unit. Mr. A. Michel Alexander, CTD, prepared the report.

During the publication of this report, Director of WES was Dr. Robert W. Whalin. COL Leonard G. Hassell, EN, was Commander and Deputy Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
feet	0.3048	metres
inches	25.4	millimetres

REVIEW OF MEASUREMENT TECHNIQUES AND PRINCIPLES WITH POTENTIAL APPLICATION FOR DEVELOPMENT OF DEVICE TO INDICATE ADEQUACY OF FRESH CONCRETE CONSOLIDATION

PART I: INTRODUCTION

1. The ideal consolidation meter would be lightweight, hand-held, battery operated, easy to use, and can be pointed at any location on the surface of freshly compacted concrete. Ideally, the apparatus would contain a digital display that reads "OKAY," or "REVIBRATE." Except for the on/off switch and a dial to set the depth of measurement, no other adjustment switches would be needed. Training to operate the device would be minimal and could be accomplished in a few minutes. The batteries would need to last many hours before needing replacement or recharging. It would work in sunshine, darkness, or rain. No representative sample would be needed, and there would be no need to wait for the results from the laboratory while the in-place concrete hardens. The concrete would remain undisturbed in its actual state of consolidation during the measurement. The concrete would not have time to harden before the results were known, and therefore, there would be no need to remove concrete after hardening.

2. A practical meter is needed. It is not likely that the ideal device is now possible, and even if the technology did exist, its high cost would probably preclude its development. Fortunately, the construction industry is not waiting for this ideal device to be developed. It will use something much more practical if the device can be used quickly, onsite, and accurately, and even if training is required. This report will deal with practical techniques rather than novel systems. However, the foregoing discussion gives a picture of an ideal device whose features should be incorporated into a practical device to the extent practicable.

Scope of Investigation

3. A literature review was performed to determine various measurement techniques which show promise as a basis for developing a suitable device. The main thrust of this review was to understand the technology for measuring

the degree of consolidation of in-place concrete, but a secondary objective was for measuring the degree to which the concrete had hardened. The techniques are based on various physical phenomena, including mechanical, optical, electromagnetic, electrical ultrasonic, radioactive-based methods, and others. Only the techniques that show promise for use in a practical device were reviewed. No theoretical concepts or novel approaches are presented here, even though some may exist and have potential.

4. This report contains an evaluation of various methods by explaining findings of various investigators, the physics behind each method, and the strengths and weaknesses of each technique. A more thorough evaluation would require a laboratory study to test the various techniques and equipment and uncover the optimum system.

Background

5. Some measurement fundamentals should be mentioned. The cost of a measurement system is based on a number of factors (Cerni and Foster 1962). Some of these are: the type, amount, and rate of data collected; accuracy required; and sophistication of equipment required. There are two basic types of data: static and dynamic. Fortunately, the degree of consolidation of the fresh concrete at rest changes slowly, if at all, and therefore this is a static measurement if made at one location. However, the statistical need to determine measurements over many locations at a rapid rate may create dynamic data. The measurement requires high accuracy and would be the most costly feature of equipment development. It is possible that the technique may require a laptop computer or microprocessor as part of the system if many measurements are needed in a short time, if any calculations are required, and if data storage is necessary. Data collection performed manually may be less expensive than automatic or semiautomatic measurements. Comments on the eventual method and type of equipment needed are beyond the scope of this report.

6. In order for a measurement system to detect the presence of some material within another material, it must be able to detect some unique property in the first material that is different from the same property of the second material. A property is some attribute or quality of a material that

is unique to that material. Since any consolidation measurement device chosen should be capable of measuring the degree to which the air that originally filled the form has been replaced by concrete, it must be sensitive to some characteristic property of air that differs from the same property of concrete. There are numerous mechanical, electrical, optical, electromagnetic, chemical, and other types of properties of air and concrete that give the two materials their distinctive characteristics.

7. An ideal way to increase the resolution of the measurement of the percentage of one material contained in another is to make use of a particular physical property whose values are widely separated for the two materials. Then the range of variation of the measurement can be many times the resolution of the measurement system. This is clearly illustrated by the optical properties of air, for example. Air is transparent to visible light, while concrete is not. That is, the degree of transparency is widely separated for the two materials. Also, the electrical properties of air are significantly different from the electrical properties of concrete. Fresh concrete is a conductor in the region of 10 to 20 ohm-metres, while air is a dielectric with a resistivity exceeding 10^{12} ohm-metres.

8. Another important measurement concept involves the means by which the subject physical quantity (amount of air, in this case) is determined, i.e., directly or indirectly (inferential). Some physical quantities cannot be directly measured and must be inferred by the direct measurement of some other quantity that is related to the desired quantity. For example, radar and pressure measurements (inferential) are used to determine the altitude of an airplane since it is impossible to directly measure the displacement of the plane off the earth's surface with a measurement tape or displacement transducer. Numerous examples can be used to illustrate direct and indirect measurements; however, for improved accuracy, direct measurements are preferred over inferential measurements when possible.

9. An important consideration in measuring consolidation of concrete is the degree to which the concrete fills the form. "One requirement for good quality concrete is proper consolidation, a process through which fresh concrete is densified by removing entrapped air" (Ozyildirim 1981). Whiting, Seegebrecht, and Tayabji (1987) report that proper consolidation would result in the improvement of the quality of concrete in a number of areas: an

increase in compressive strength, an increased bond strength to reinforcing steel, an increased resistance to freezing and thawing, and a decreased permeability to chloride ions.

10. Entrapped air, also known as "accidental air," is defined by ACI 116R-90 as "air voids in concrete which are not purposely entrained and which are significantly larger and less useful than those of entrained air, 1 mm or larger in size." Entrained air is defined by ACI 116R-90 as "microscopic air bubbles intentionally incorporated in mortar or concrete during mixing, usually by use of a surface-active agent; typically between 10 and 1000 μm in diameter and spherical or nearly so." Entrapped air should largely be removed from concrete during vibration. The proper amount of entrained air in concrete contributes to workability and frost resistance. An excess amount of air will cause the concrete strength to be reduced significantly. For every 1 percent increase in air, there is an approximate 5 percent loss in compressive strength. The total amount of air must be kept within a narrow range, and therefore, the accurate determination of air content becomes an important measurement parameter (Nasser and Whatley 1988).

11. The three standard methods for measuring air content of fresh concrete are ASTM C 231, C 173, and C 138). However, none of these is suitable for measuring the degree to which concrete fills the form after being consolidated. Although samples that are taken from the mixer may be properly consolidated and their air content accurately measured with one of the methods mentioned, the resulting test value does not necessarily represent the effectiveness of consolidation of the concrete in the forms. However, the consolidated samples do yield the target value of the air content desired in the placement since the entrapped air has been largely removed and it is primarily the entrained air that remains. It is the nature of the consolidation process to largely expel the entrapped air before significantly affecting the entrained air. Since some concrete is undervibrated, an actual measurement of degree of consolidation in place is needed rather than an assumption about the quality of the consolidation process. The hardened concrete can be sampled and tested in the laboratory by the techniques described in ASTM C 457, but the test results cannot be determined quickly. An in-situ assessment of degree of consolidation would complete the quality

control and quality assurance through the final stages of concrete production, placement, and consolidation.

12. The gravimetric method (ASTM C 138) uses a mathematical calculation based on a measurement of the masses and densities of each of the constituents: cementitious materials, water, fine and coarse aggregate, and the mass of the actual concrete mixture as taken from the mixer. The theoretical air-free density and the actual density are then used to calculate the air content. This is an inferential measurement of air content, and the results are highly dependent on the accuracy of the measurements of the mass and density of each component of the mixture. This test is not normally conducted in the field as it depends on accurate knowledge of the mixture proportions and properties (Khayat et al. 1990).

13. The volumetric method (ASTM C 173) is based on displacing the air in the concrete with water. This technique is dependent on the density of air being lower than that of water, and it has the advantage of being a direct measurement. Concrete is placed in a container, and the water is poured over the concrete to a definite level. The container is then sealed and the air is separated and rises to the top and is replaced by water through a process of shaking and rolling of the container. The determination of the air content is measured on a calibrated scale as the drop in height of the water column. Various investigators have criticized volumetric measurements as taking too long for the air bubbles to rise (Ozyildirim 1990). Usually, the measurement is made within 15 minutes to reduce the time problem in the field.

14. The pressure method (ASTM C 231) is based on Boyle's law. Boyle's law states that for a given increase in pressure, the volume of a gas is reduced proportional to the increase in pressure. In fresh concrete, air is the gas referred to and is the only component of the mixture that is highly compressible. The method is not suitable for concretes containing aggregate particles of high air contents. The concrete is covered by water within a vessel capable of being pressurized. The pressure above the water is then increased. For type A meters, the lowering of the water column indicates the air content by means of a calibrated scale. For type B meters, the air content is read directly from a calibrated pressure gage. The method is considered to be a direct measurement system.

15. There is an important need for an in situ meter. Ideally one would like to measure the air content in place after the consolidation process but while the concrete is still able to respond to vibration. One would then have time to revibrate the concrete if the consolidation was insufficient before the concrete hardened. Also, as a by-product of the device, it might be possible to measure some property of the fresh concrete that would indicate the presence and rate of hydration prior to hardening.

16. The ability to measure the degree of consolidation of fresh concrete in situ before, during, and after consolidation could be an important aspect of quality control and quality assurance. The in-place measurements would significantly improve the quality-control and quality-assurance processes contrasted with the preplacement measurements taken on concrete taken from the mixer. Also, the concrete placement could be checked in numerous locations before hardening, yielding better average information about the actual degree of consolidation of the hardened concrete. The uniformity of the consolidation process throughout the placement could also be determined, permitting improvements in the consolidation where needed.

17. Although it might appear desirable to have separate measurements on the entrained and entrapped air content in place, the measurement of total air content would probably be sufficient to evaluate the degree of consolidation achieved. However, one would need the air content (target air content for the in-place concrete) in the concrete from the mixer after it is properly consolidated in an air meter in order to accurately interpret the in-situ measurements. This knowledge could be obtained by sampling concrete in accordance with ASTM C 172 and testing it in accordance with one of the ASTM air content tests mentioned above. The sample air content could then be used as the in-situ target air content. In-situ air content measurements greater than the target air content would indicate the need for additional vibration. For example, if the total air content measured 9 percent and the sample had measured 7 percent, then it would follow that the in-situ concrete contained 2 percent of unintentionally entrapped air and more consolidation was necessary.

PART II: DESCRIPTION AND EVALUATION OF VARIOUS TECHNIQUES

Electrical Resistivity

18. The electrical resistivity of cement paste lies in the region of 10 to 13 ohm-metres at 23 °C while most aggregates will lie above 300 ohm-metres (Whittington, McCarter, and Forde 1981). Because the resistivity of aggregates is several orders of magnitude larger than that of paste, most of the electrical current will travel through the paste. The resistivity of fresh concrete is about three to four times the resistivity of the cement paste due to the fractional volume of the high resistivity aggregate. McCarter, Forde, and Whittington (1981) and Calleja (1952) attribute the electrical resistance of cement paste to two primary factors. One is the ionic conductivity of the cement-water solution which depends on the ion concentration, type of ions, and temperature. The other factor, electronic conduction, is due to increasing mechanical resistance and cohesiveness of various compounds as setting progresses. For the purposes of developing a consolidation meter, the latter factor would not be of interest. Gunnink (1988) reports that the electrical resistivity is related to the air content and the pore size distribution in concrete. Kikkanen (1962) concluded that concretes are conductors similar in nature to electrolytes, and reported data showing that the temperature coefficient for the electrical conductivity of fresh paste is of the same order of magnitude as that of common electrolytes. The temperature coefficient is negative, that is, an increase in temperature causes a decrease in resistivity and vice versa.

19. The passage of a direct current (DC) through an electrolyte causes polarization, which is the establishment of a potential at the electrodes that opposes the applied potential. This complicates the measurement of the specimen resistance, requiring that an alternating current (AC) be used for the measurement rather than DC. Calleja (1952) stated that the frequencies used in the determination of the electrical resistance of cement paste using AC resistance measurements should not be below 1 kHz.

20. Also, it is not sufficient to make a voltage-to-current ratio measurement, a simple magnitude measurement, to determine the resistance. The polarization effect creates a capacitive reactance that is in parallel with

the specimen resistance. This requires that an impedance measurement be made rather than the simpler resistance measurement in order to separate the desired resistive portion from the two components of impedance. Impedance measurements require an electrical bridge balance involving phase as well as magnitude adjustments. Complex mathematics (real and imaginary variables) are required to describe the measurement rather than just algebraic expressions as in the first case. A review of the literature and the mathematics that describe the measurement is being drafted (Alexander in preparation).

21. Resistivity measurements have significant potential in the study of concrete properties. A possible use of concrete resistivity data includes quality control of concrete prior to hardening. Although outside the scope of this report, it may be possible to use the electrical resistivity of concrete as a measure of its degree of hydration and to determine the magnitude and variability of the air content throughout a concrete placement. The graph of increase of electrical resistivity with time follows the same general shape as the strength versus time curve for concrete (McCarter et al. 1981).

22. Numerous factors influence the resistivity of fresh concrete: the mixture proportions, water-cement ratio (w/c), concrete temperature, storage environment, rate of hydration, and air content. These factors complicate the in-place measurement of the air content. A possible solution might be to obtain a representative sample from the mixer, consolidate it properly by vibration, and measure the resistivity of the sample to determine the standard values for the factors mentioned above. The same sample that is used to determine air content should be used. Then the resistivity measurement in the concrete placement would differ only by the degree of consolidation assuming that both measurements are made at the same temperature and time. Field resistivity measurements could be made automatically by computer in order to speed up the process.

23. The resistivity technique is a nondestructive measurement provided the probe is configured correctly. Small wires can be used for the two electrodes, which would produce minimum disturbance in the fresh concrete. No sample would need to be obtained from the placement. It is also suitable for use in numerous locations and depths in the fresh concrete.

Nuclear Methods

24. A nuclear density gage (NDG) has the accuracy to measure the density of concrete to within 1 percent. Since air content is linearly related to density, then it should be possible to measure the air content to within a similar accuracy. However, the relationship can only hold true if the constituent densities and mixture proportions are known (Nasser and Dolan 1989).

25. A disadvantage of the NDG is that the air content cannot be measured directly but must be inferred by a density measurement. Other disadvantages include the problems involved with safety requirements and training needed for implementation of a nuclear device (Lee and Eggert 1978). The equipment is also heavy and bulky. Advantages are that the concrete density can be measured in place and nondestructively. The measurement is nondestructive in the sense that the condition of the fresh concrete is not effectively disturbed when the correct type of probe is used. The device is rugged and reliable. The nuclear method is a tried and tested technique that is practical and has been widely used to determine concrete density. Standard test methods are given in ASTM C 1040. The state of the art of nuclear density measurements is far more advanced than any of the nonnuclear methods.

Fiber Optics

26. The in-place determination of air-void characteristics of fresh concrete can purportedly be determined with a device that uses a fiber optic cable for a sensor (Ansari 1991). The development of this system was sponsored by the Strategic Highway Research Program (SHRP) (Ansari 1990, 1991a, 1991b). The system is based on Snell's law. A light source from a laser illuminates one end of the fiber optic cable while the opposite end containing the sensor is inserted into the fresh concrete. The air content of the fresh concrete is measured by determining the intensity of the reflected light at the sensing end, and the amount of reflected light is related to the percentage of air in the concrete. The ratio of the amount of reflected light to the refracted light at the measurement end of the cable is related to the indices of refraction of the fiber optic cable and the material at the

reflecting interface. Total refraction (no reflected light) occurs when the indices of the two materials are identical. The index of refraction of the glass is 1.4. Air has an index of refraction of 1.0003, and because of the large difference in the index of refraction of the two materials, most of the light will be reflected when the measurement interface is inside an air bubble. The average index of refraction of fresh concrete is believed to be 1.35, which means that the index is close to that of the glass fiber. In this case, most of the light will be refracted with little reflected.

27. Calibration of the apparatus first consists of holding the probe in the open air to establish the upper end of the scale or 100 percent air. The first operation seems logical; however, the lower end of the scale is found by holding the probe in fresh concrete for 10 sec. It would seem that the lower end of the scale should be established by holding the probe in contact with something having the same index of refraction as that of the fiber optic cable. Then there would be no refraction and 0 percent air would be indicated. A measurement in concrete should then fall between 0 and 100 percent air content extremes.

28. It is not sufficient to make one reading at a given location in the placement. Because the size and distribution of air bubbles vary throughout any mixture, enough readings must be taken to obtain a proper statistical sample of the population of bubbles. The air content measured is then the average air content measured over a 10-sec time frame and over the particular length of travel of the probe in the fresh concrete. The probe must be inserted into the fresh concrete and moved forward a few inches while readings are taken at a rate of about 30 samples per sec. This again appears logical, but it would require a rigorous theoretical study to determine the proper rate of sampling, the length of traverse in the fresh concrete, the rate of movement of the probe, and the diameter of the end of the fiber optic cable in relationship to the size and distribution of bubbles in the concrete. Also, even if the physics of the system is completely valid and understood, it is still necessary for independent and unbiased investigators in the research community to apply the scientific method of falsification to the hardware to refute or verify the claims of the inventor.

29. This system is advantageous in that it gives a direct measurement of the air content. It can be adapted to exist as a small portable, hand-held

probe with computer data acquisition and processing. The probe can be made rugged by encasing the fiber in a stainless steel sleeve. It does not produce a depression in the concrete since a sample is not required from the placement. The test is essentially nondestructive since the surface blemish can be easily floated. The calibration purportedly takes out the influence of the type and amount of various constituents. Personnel can be trained to use the apparatus in about 30 minutes. The cost for a system including a laptop computer is about $2,000. Tests (Ansari 1990) show that the fiber optic measurements agree well with those determined by the ASTM standard methods for determining air content in fresh concrete.

Ultrasonics

30. The testing of hardened concrete by ultrasonic velocity measurements is a standard ASTM procedure, ASTM C 597. "However, for the measurement of fresh concrete this method is still in its infancy" (Winden and Brant 1977). Winden and Brant used ultrasonic measurements from the British manufactured Pundit to perform quality control checks on the workability and premature setting in the placement of fresh concrete in the North Sea. They found that the ultrasonic velocity was dependent upon environmental temperature and the temperature of the concrete at initial set, w/c, type of cement, and types of chemical admixtures. Jones (1951) reported graphical data of longitudinal pulse velocity measurements of fresh concrete against age. The curves start at approximately 4,000 fps* when the fresh concrete is about 4 hr old, and the velocity increases rapidly for a few hours during the hydration process before the rate of increase drops significantly. Whitehurst (1951) tested very stiff fresh concrete 2 to 4 hr old with the Soniscope to correlate pulse velocity with time of setting. Tests were attempted immediately after placement, but the signal could not be detected until some time had passed. The point where the rate drops significantly is believed to be the time of setting. Cheesman (1951) made measurements on fresh concrete 5 hr after mixing to correlate pulse velocity with compressive strength and

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 3.

found a linear relationship. These investigations demonstrate that the pulse velocity is an important indicator of the hydration process and that time of setting can be determined and strength can be predicted to some unknown degree of accuracy.

31. Each of the previous tests was made after completion of the consolidation operation and did not reflect the changes that occurred as the concrete was densified and the entrapped air was removed by the process. The author made some resonant frequency measurements to test the degree of consolidation and found that the resonant frequency increased 300 percent during the consolidation process (Alexander 1977). The indications were that the removal of air increased the velocity of propagation of the reverberating stress wave in the concrete. Concrete was placed in a 1- by 1- by 1-ft wooden box, and the system was excited to longitudinal resonance by igniting the fuse of a small conventional firecracker with an electronically heated Nichrome wire positioned inside the placement. This mechanical impulse then excited longitudinal resonance of the fresh concrete between the sides of the box. Tap water gave a frequency of 9,600 Hz while the consolidated concrete yielded a frequency of 400 Hz. Since the velocity of water is 5,000 ft per sec, this indicated that the velocity in the concrete was only 1/24 of the velocity of water or 208 ft per sec. Since the resonant frequency is dependent on the longitudinal wave velocity, it is expected that sonic or ultrasonic longitudinal pulse velocity measurements would have indicated a similar pattern of behavior.

32. In addition to the pulse velocity being related to the air content, it is also a good indicator of the rate of hydration. Not only might ultrasonics be used by a consolidation meter to check the magnitude and uniformity of the air content throughout the placement at a given time, but it might also be used against time as a means to check the degree of hydration before hardening.

33. An advantage of ultrasonics lies in the accuracy and resolution of the measurements. The range of measurement is many times the resolution of the measurement, which is a desirable characteristic of any technique. A disadvantage is that a larger power supply might be needed than is presently used for hardened concrete, and the device would be heavy and bulky. However, a transducer pair (transmitter and receiver) connected to a probe could be

hand-held with the electronic equipment placed off to one side. Another disadvantage is that the velocity is a function of variables other than air content. It may be dependent on the mixture proportions, the rate of hydration, and other factors. Fortunately these variables will remain constant during the consolidation process. The transducers should be kept as small as possible to create a nondestructive test method, but it is not currently known how small the transducers could be and still be efficient. For simplicity, a digital readout could be used to measure the time of arrival, or the reading could be converted to calibrated index values to represent a particular degree of consolidation. It may be necessary to determine standard values of the pulse velocity for each mixture by taking a sample of the fresh concrete that is used for the air content measurements and consolidating it properly before making measurements in the placement.

Lasers

34. A new technique currently under research involves the use of liquid nitrogen to freeze the fresh concrete before the frozen core is extracted (Hansen 1991). A laser instrument is then used to test the air content by rotating the specimen on a lathe bench. Reproducibility is one of the major problems experienced with the laser. Other disadvantages are the destructive nature of the test, the time required for the results, and the problems encountered to test in numerous locations. Results are in agreement with air content tests made with an image analyzer; however, further research is needed.

PART III: CONCLUSIONS AND RECOMMENDATIONS

35. It is important that quality control and quality assurance be uninterrupted through the placement and consolidation process. Nondestructive testing technology has advanced significantly, and if applied to fresh concrete, it may be capable of significantly improving quality control and quality assurance.

36. The ideal consolidation meter should possess most or all of the following qualities.

a. Lightweight, rugged, and portable.

b. Small, nondestructive, hand-held probe measurement.

c. Accurate, with low cost.

d. Easy to use, requiring little training.

e. Rapid measurement.

f. Capable of covering many locations in the placement.

g. Direct measurement of degree of consolidation as opposed to inferential measurement.

h. Rapid and easy to understand results.

i. Battery operated.

j. Operate well under adverse environmental conditions.

k. Not influenced by variables other than air content.

A literature review has revealed various techniques that have potential as a basis for a device to indicate degree of consolidation. The fiber optic system is a direct measurement technique and shows considerable potential. Although the fiber optic system is new and time has not permitted verification by independent investigators, it has the potential of being the closest system to the ideal meter. It is recommended that a determination be made as to whether the physics of the technique is valid, either before or while the device is being tested extensively in the laboratory.

37. The author has had experience in the area of transducer development for ultrasonics for hardened concrete and believes that transducers could be built which would have the energy necessary to permit early time velocity measurements in fresh concrete prior to consolidation. Although there have been no investigations to study the degree of consolidation with ultrasonics, there is evidence that it would be a sensitive indicator. One might use the

ultrasonic technique to determine if the concrete is hydrating properly before final setting and to give predictions of the future compressive strength. A desirable attribute of the ultrasonic method is that the velocity is directly related to the mechanical properties of a material. Ultrasonics show considerable potential to provide important quality control measurements on fresh concrete prior to hardening and more research should be performed in this area.

38. Although the data are limited in the area of fresh concrete, resistivity measurements offer considerable potential for providing an early time prediction of concrete compressive strength. An advantage of resistivity measurements is the measurement of accuracy and resolution of the technique. However, it has never been used specifically to measure air content, and its sensitivity is not known. Also, there are many variables that influence resistivity measurement, and these must be properly addressed. In addition, the design and development of an automatic measurement system would be needed. WES can presently make manual measurements in the laboratory, but the technique is too slow for field measurements. Additional research is needed on electrical resistivity measurements of fresh concrete since resulting benefits could be significant.

REFERENCES

Alexander, A. Michel. 1977. "Study of Vibration in Concrete," Report 3, "Mechanics of Motion of Fresh Concrete," Technical Report 6-780, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

__________. "On the Theory, Application, and Review of Electrical Resistivity Measurements on Concrete," Technical Report in preparation, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

American Concrete Institute. 1990. "Cement and Concrete Terminology," Publication SP-19 (90), 68 pp, Detroit, MI

__________. 1991. "Guide for Consolidation of Concrete," ACI 309R, ACI Manual of Concrete Practice, American Concrete Institute, Detroit, MI.

American Society for Testing and Materials. 1991. Annual Book of ASTM Standards, Vol 04.02, American Society for Testing and Materials, Philadelphia, PA.

a. Designation C 138. "Standard Test Method for Unit Weight, Yield, and Air Content (Gravimetric) of Concrete."

b. Designation C 173. "Standard Test Method for Air Content of Freshly Mixed Concrete by the Volumetric Method."

c. Designation C 231. "Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method."

d. Designation C 457. "Standard Test Method for Microscopical Determination of Parameters of the Air-Void System in Hardened Concrete."

e. Designation C 597. "Standard Test Method for Pulse Velocity Through Concrete."

f. Designation C 1040. "Standard Test Methods for Density of Unhardened and Hardened Concrete In Place By Nuclear Methods."

Ansari, Farhad. 1990. "A New Method for Assessment of Air Voids in Plastic Concrete," Cement and Concrete Research, Vol 20, No. 6, pp 901-909.

__________. 1991a. "Fiber-Optic Air-Void Meter," SHRP-IDEA 011, SHRP-ID/UWP-91-1511, Research Products and Technical Progress, SHRP-ASCE Meeting, 8-10 Apr 91, Denver, CO, pp. 59-64.

__________. 1991b. "Rapid In-Place Air Content Determination in Fresh Concrete," Concrete International, Vol 13, No. 1, pp 39-43.

Calleja, J. Mar 1952. "New Techniques in the Study of Setting and Hardening of Hydraulic Materials," Journal of the American Concrete Institute, Proc. Vol 23, No. 7, pp 525-536.

Cerni, R. H., and Foster, L. E. 1962. Instrumentation for Engineering Measurement, John Wiley and Sons, New York.

Cheesman, W. J. Taken from DISCUSSION in following reference: Whitehurst, E. A. 1951. "Use of the Soniscope for Measuring Setting Time of Concrete," American Society for Testing and Materials, Proc. Vol 51, pp 1166-1176.

Gunnink, B. W., Enustun, B. V., and Demirel, T. 1988. "Determination of the Pore Structure of Porous Materials Using Electrical Conductance," Particulate Science and Technology, 6(1): 105-117.

Hansen, Will. Apr 1991. "Freeze Coring of Fresh Concrete and Air Void Measurement," SHRP-IDEA 007, SHRP-ID/UWP-91-511, Research Products and Technical Progress, SHRP-ASCE Meeting, Denver, CO, pp 37-41.

Jones, R. 1951. "The Non-Destructive Testing of Concrete," Reinforced Concrete Review, Presentation given at Reinforced Concrete Association in London on 13 Dec 50, Vol 2, No. 5, pp 315-328.

Khayat, Kamal H., Nasser, K. W., and Hester, Weston T. 1990. "Alternative Method to Measure Air Content in Fresh Concrete," ACI Materials Journal, Vol 87, No. 4, Title No. 87-M38, Jul-Aug 90, pp 355-362.

Kikkannen, P. 1962. "On the Electrical Properties of Concrete and Their Application," Valtion Teknillinen Tutkimuslaitos, Tiedotus, Sarja III, Rekennus 60, pp. 175.

Lee, Philip L., and Eggert, Glenn J. Mar 1978. "Development of a Device for Continuous Automatic Monitoring of Consolidation of Fresh Concrete," FHWA-RD-78-27, Rexnord, Inc., Milwaukee, WI, pp. 94.

McCarter, W. J., Forde, M. C., and Whittington, H. W. Mar 1981. "Resistivity Characteristics of Concrete," Proceedings of the Institution of Civil Engineers, Part 2: Research and Theory, Vol 71, pp 107-117.

Nasser, Karim W., and Dolan, Dale E. Mar-Apr 1989. "Considerations for Potential Use of Nuclear Density Gages on Concrete," ACI Materials Journal, Title No. 86-M14.

Nasser, K. W., and Whatley, B. D. 1988. "Mini Air Meter for Fresh Concrete," Concrete International: Design and Construction, Vol 10, No. 3, pp 43-46.

Oxyildirim, H. Celik. Jan 1981. "Evaluation of a Nuclear Gage for Controlling the Consolidation of Fresh Concrete," Report No. FHWA/VA-81/41, Federal Highway Administration.

__________. Mar 1990. "Comparison of Air Voids Content Measurements in Fresh Versus Hardened Concrete," Report No. FHWA/VA-R23, Virginia Department of Transportation, pp 1-26.

Whitehurst, E. A. 1951. "Use of the Soniscope for Measuring Setting Time of Concrete," American Society for Testing and Materials, Proc. Vol 51, pp. 1166-1176.

Whiting, D. Seegebrecht, G. W., and Tayabji, S. 1987. "Effect of Degree of Consolidaticn on Some Important Properties of Concrete," SP-96, Consolidation of Concrete, American Concrete Institute, Detroit, MI, pp 125-160.

Whittington, H. W., McCarter, J., and Forde, M. C. 1981. "The Conduction of Electricity Through Concrete," Concrete Research, Vol 33, No. 114, pp. 48-60.

Winden, N.G.B. van der, and Brant, A. W. 1977. "Ultrasonic Testing for Fresh Mixes," Concrete, Vol 11, No. 12.

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